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**NAVAL AIR SYSTEMS COMMAND
MAINTENANCE TECHNOLOGY PROGRAM
NDI SURVEY OF COMPOSITE STRUCTURES**

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VOUGHT CORPORATION
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) As part of the Naval Air Systems Command Maintenance Technology Program, a survey was made of DoD, NASA, NBS, Industry and the R&D Community reviewing and analyzing the current status of current nondestruction inspection (NDI) technology for composites. The survey is aimed at contributing information which will assist in defining NDI requirements for the organizational, intermediate, and depot levels of maintenance. The investigation reported herein		

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covers a survey to determine the state of NDI technology for composite materials and an analysis of the survey results in terms of maintenance requirements for naval aircraft.

This review and analysis of the status of current NDI technology covers the experience of DoD, NASA, NBS, Industry, and the R&D community. A range of composite materials and constructions, damage classification, repair procedures, and NDI techniques were included in the survey. Twenty-one different NDI methods were examined and ranked in terms of effectiveness. Twelve types of composite damage and five different repairs were considered during the investigation. Conclusions included definitions of the most frequently encountered types of construction, the five NDI techniques considered essential, specific technique recommendations for specified damage to specified configurations, and technique recommendations for verifying specific types of repairs.

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FOREWORD

This report covers the work performed during the period from May, 1978 to April, 1979 under Navy Contract N62269-78-M-6391. This work was administered by the Naval Air Systems Command under the direction of Mr. A. J. Koury, AIR-4114C. The effort was conducted by Dr. S. A. McGovern, Vought Corporation. Key technical efforts were performed by Mr. R. C. Knight and Mr. C. L. Shank, Vought Corporation.

The systems concept for aircraft composite material maintenance was established and pioneered by the Naval Air Systems Command (Mr. A. J. Koury, AIR-4114C). This concept encompasses damage assessment methodology, repair/replacement techniques, repair verification and support definition. Effective nondestructive inspection (NDI) is basic to this concept and will reduce the time burden for composite maintenance/support, enable detection of imminent failure and achieve a range of cost savings for materials, energy and manpower. The approaches initiated under the Naval Air Systems Command Maintenance Technology Program to establish an effective NDI capability at the earliest possible date include the following:

- o Implementation and application of new NDI technology such as neutron radiography, holography, piezoelectric polymer sensors, ultrasonics, exo-electron emission and real-time imaging.
- o On-site demonstrations for aircraft applications.
- o Review and analysis of the status of current NDI technology for composites.

The latter approach is the subject of this report and covers the NDI experience of DoD, NASA, NBS, Industry and the R&D community. A range of composite materials/configurations, damage classification, repair procedures and NDI techniques were included in the survey. Twenty-one different NDI methods were examined and ranked in terms of effectiveness. Twelve types of composite damage and five different repairs were considered during the investigation. A preliminary status report of the findings contained herein was presented during the Composite Material Maintenance/Repair Workshop (September, 1978), sponsored and conducted by the Naval Air Systems Command (AIR-4114C).

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NDI SURVEY OF COMPOSITE STRUCTURES

1.0 INTRODUCTION

More effective maintenance enabling reduced support requirements for both current and planned naval aircraft having composite structure is a goal of the maintenance technology program established by the Naval Air Systems Command (AIR-4114C). A high priority task initiated under this program is aimed at defining nondestructive inspection (NDI) requirements and procedures for the organizational, intermediate and depot levels of maintenance. The investigation reported herein covers:

- o A survey to determine the state of NDI technology for composite materials
- o An analysis of survey results in terms of maintenance support requirements for naval aircraft.

The survey questionnaire (Appendix A) covers damage classification, repair procedures and NDI. The percentage of responses received to the one hundred three questionnaires distributed was about thirty per cent. The distribution categories and number of responses are shown below in Table 1.1.

TABLE 1.1
QUESTIONNAIRE AND RESPONSE DISTRIBUTION

<u>CATEGORY</u>	<u>NUMBER SENT</u>	<u>% OF TOTAL</u>	<u>NUMBER OF RESPONSES</u>	<u>% OF TOTAL</u>
Academic	25	24.3	3	9.7
Air Force	16	15.5	2	6.5
Army	7	6.8	2	6.5
Industry	36	35.0	17	54.7
NASA	2	1.9	1	3.2
NBS	2	1.9	0	0
Navy	<u>15</u>	14.6	<u>6</u>	19.4
Totals	103		31	

2.0 DESCRIPTION OF NDI TECHNIQUES

Composite materials offer a number of potential advantages for aircraft applications which include reductions in weight, fuel conservation, and life cycle cost reduction. However, these materials also introduce more requirements for inspection and Quality Assurance. For metallic structure, one is usually most interested in the detection of a crack or discontinuities that could coalesce to a crack; whereas for composites the list is expansive, including improper cure, resin rich or poor areas, fiber misalignment, unbonds, inclusions, machining damage, impact damage, fastener fretting and pullout, and environmental degradation. To detect and characterize this wide range of defects requires a number of specialized NDI techniques.

Since the effect of a resin poor defect is potentially different from an impact damage defect, it is essential that NDI techniques that have the potential of differentiating between these and other types of defects be employed.

NDI techniques are used to detect and characterize critical and sub-critical defects during and after processing, after fabrication, and in-service, to monitor initiation and propagation of damage during mechanical testing; and to map and characterize damage zones.

For purposes of these discussions, NDI techniques are grouped into the following general categories: production and postproduction shop methods; service depot inspection techniques; field inspection techniques; laboratory techniques (which, with further development, may fall into either of the three previously mentioned technique areas); and passive NDI techniques to be used for the detection and monitoring of damage initiation and propagation during mechanical testing. It is fully recognized that a number of these techniques, such as ultrasonic, may be included in each of these categories. But, in general, the types of defects that are sought and the restrictions placed upon the inspection techniques are different for each category. Furthermore, this type of categorization aids in identifying existing and possible future NDI "gaps".

Techniques within each of these categories are sensitive to different types of defects and/or adaptable to a particular testing environment. Shop

inspection techniques would be more sensitive to layup, resin formulation, and curing abnormalities, whereas, service depot and field inspection methods are more sensitive to matrix cracking and delaminations resulting from impact and/or fatigue damage. However, shop techniques must also be sensitive to typical fabrication defects such as handling, hole splintering, and bondline defects. Shop techniques, in general, are less restricted with respect to access of the part to be inspected, whereas service depot inspections allow only partial component disassembly and field inspections must be performed while the part is in the fully assembled configuration making part access a serious limitation and highlighting the need for an in-situ damage sensor. Mechanical test monitoring techniques are generally sensitive to the same damage types as in-service methods, but are subject to even more rigorous constraint. The techniques must be strictly passive, in order that the outcome of the test not be affected, and real-time to allow direct feedback to the test while it is in progress (a more complete discussion of this area is contained later in this section).

A tentative list of shop, service depot, field, and laboratory NDI inspection methods (excluding monitoring and bulk property measurement techniques) that were considered for evaluation in this program is as follows:

1. Ultrasonic pulse echo
2. C-scan
3. Thru transmission-immersed
4. Thru transmission
5. Sonic resonator
6. Low frequency air coupled
7. Eddy sonic
8. Eddy current
9. X-Ray
10. Neutron Radiography
11. Penetrant
12. Thermochromatic coatings
13. Visual or optical
14. Tap testing
15. Thermography (Video or Vibro)

16. Holography (Optical) Laser
17. Acoustic Emission
18. Microwave
19. Dielectric
20. Ion graphing
21. Holography (acoustic)

This list of techniques should really consist of only nineteen techniques. Techniques 2, 3, and 4 should have been listed as ultrasonic through transmission and not as three separate techniques. A discussion of how the data was handled is found in the appropriate paragraphs in Section 5.0.

As stated earlier, most of the above inspection techniques are applicable to more than one inspection category. This is because many techniques are sensitive to several different types of defects and also because there is an overlap in the types of defects found in each of the four inspection areas (lab, shop, service depot, and field).

2.1 NONLABORATORY NDI TECHNIQUES

The following section is devoted primarily to nonlaboratory techniques that have applications to shop, service depot, and field inspections. Subsequent sections describe laboratory techniques, material properties measurement techniques, and techniques applicable to real-time monitoring during mechanical testing. Whenever possible, general descriptions of test methodology precede specific descriptions of inspection techniques.

2.1.1 Optical Methods

For the successful application of optical inspection techniques the part to be inspected must be optically transparent and/or have absorption coefficient or index of refraction abnormalities associated with the presence of defects.

The two basic methods of optical inspection employ through-transmission and reflection of light. The basic technique of the through-transmission method is to illuminate one surface of the material and measure the amount of light received on the opposite side. In the reflection method, the amount of light reflected from the material's surface is measured. The presence of a defect at a particular location is indicated in both cases by a significant change from the normal value in the measurement amount of received light when the defect location is illuminated.

For the case of graphite/epoxy composites, which are essentially opaque, through-transmission is of little practical use. The prime application of optical inspection techniques will be for surface inspection. By use of oblique incident light viewed from normal and oblique perspectives, surface abnormalities can often be enhanced. The surface can be viewed with the unaided eye, or viewing can be aided with optical equipment which magnifies the image for greater detail. Defects in composites which may be detected optically include matrix crazing and cracking, laminate wrinkles, surface delaminations, gouges, dents, and abrasive wear. The detectability of these defects is, of course, highly dependent on the type of surface coating (paint, flame spray, aluminum screen, etc.) which has been added to the composite surface.

2.1.2 Tap Testing

Although seemingly crude in its approach, tap testing nevertheless is a commonly used NDI technique. Actually, many of the concepts of ultrasonics are being employed with the human ear as the receiver and the brain as the data analysis device. The results are potentially powerful, but not analytically quantitative and subject to a wide variability in reliability. Since the use of this technique is wide spread, it is included in this survey. To aid in the reliability and reproducibility of the test data, the special tapping hammer can be used to induce repeatable amounts of tapping energy. The technique is often used in conjunction with other techniques as a first step following visual inspection.

2.1.3 Conventional Ultrasonic Techniques

A number of ultrasonic inspection techniques are widely employed for composite NDI. Basically all of these specialized techniques involve the detection of ultrasonic wave interactions with material defects and/or abnormalities. Generally, ultrasound is coupled with the part via a liquid. The two liquid-coupled ultrasonic test techniques most employed in nondestructive materials evaluation are referred to as contact and immersion. The names describe the manner in which the ultrasonic transducer is coupled to the surface of the material. When the material being evaluated is immersed in a liquid, the transducer is acoustically coupled to it through the intervening liquid and

the technique is called immersion testing. An advantage of immersion testing is its adaptability to automatic scanning and recording. Immersion testing permits easier scanning of irregularly shaped test materials and provides good nearsurface resolution. It can be modified through use of a "bubbler" or portable liquid column which permits use of immersion techniques in a quasi-contact mode.

The sensitivity of any ultrasonic technique to the presence of a defect is dependent upon several factors. One of these factors is the wavelength of sound used, since the shorter the wavelength the smaller the defect that can be detected. The wavelength is directly related to the test frequency. Frequencies normally employed for liquid-coupled ultrasonic inspection range from 1 megahertz (MHz) to 25 MHz. (Higher frequencies result in shorter wavelengths; for example, a 10 MHz sound beam has approximately a 0.025 cm wavelength in graphite/epoxy.) Other factors include transducer size, focus, alignment, and others. A general "rule of thumb" is that the minimum detectable defect size is about 1/2 the diameter of the transducer used.

There are basically four commonly employed liquid-coupled ultrasonic inspection techniques applicable to composite inspection. These are illustrated in Figure 2.1, and include pulse-echo contact, pulse-echo immersion, pulse-echo immersion reflector-plate, and immersion through-transmission test methods.

- o Pulse-Echo Techniques (either contact or immersion) utilize a single transducer as the transmitter and the receiver of the ultrasonic energy. Although immersion coupling is occasionally employed, contact coupling via a thin layer of ultrasonic couplant, glycerin, or oil is more commonly applied. With this test method, the information regarding internal soundness of the composite is displayed on an oscilloscope viewing screen. The horizontal scale on the viewing screen represents time or distance, and the vertical scale, amplitude. Therefore, unbond conditions within the composite are displayed as vertical deflections, whose time of occurrence corresponds to their location.

There are several disadvantages associated with contact test methods that can make implementation and interpretation difficult. The amount of pressure applied to the transducer affects the amplitude of the

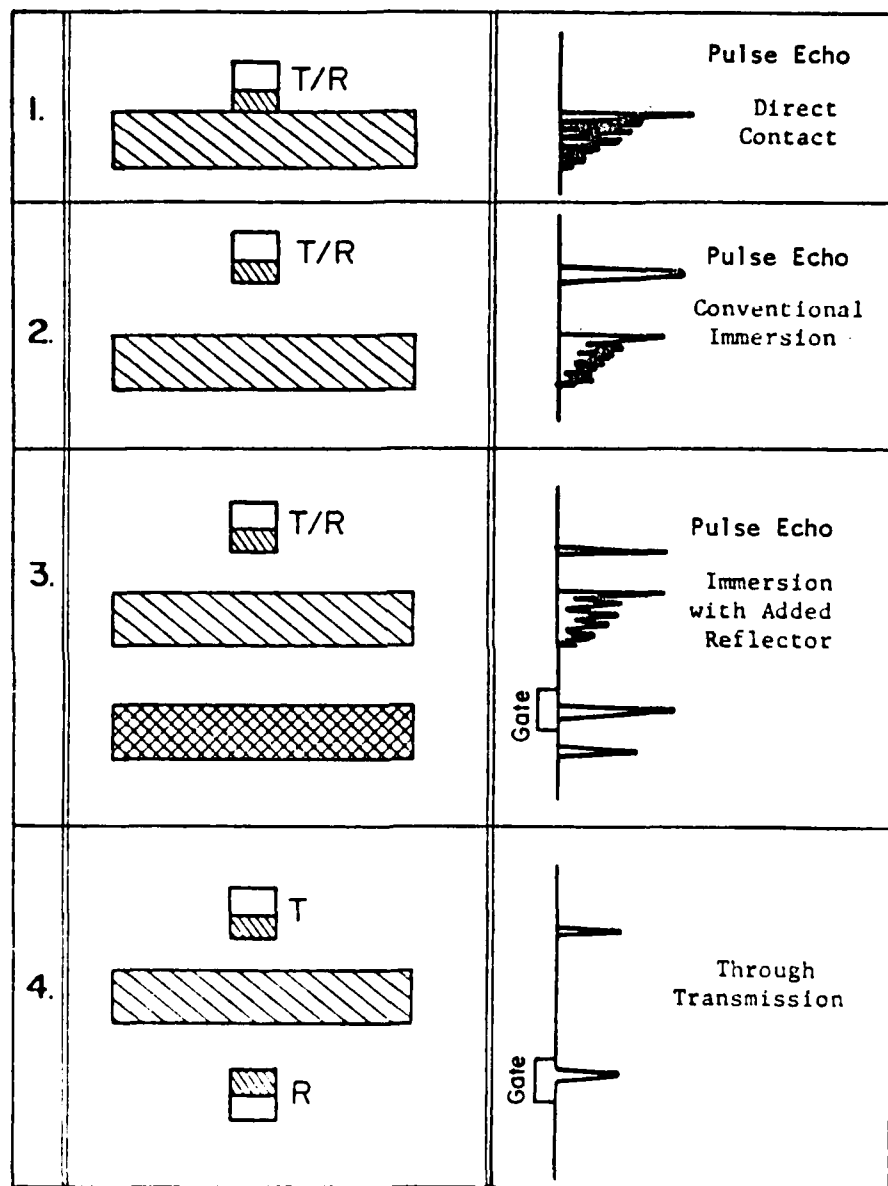


Figure 2.1 Liquid Coupled Ultrasonic Techniques for Composite Inspection

signal received from a defect signal. Depending upon the thickness of the composite, the width of the initial pulse signal may cover the entire material thickness as displayed on the viewing screen. The test results are highly dependent upon operator interpretation. And finally, automated inspection is not easily achieved. Due to these disadvantages over through-transmission and reflector plate techniques, contact pulse-echo is usually employed only when part access and/or geometries preclude use of immersion techniques.

- o The Through-Transmission Immersion (TTI) Test Method has been the most widely utilized for evaluation of composite materials. The through-transmission method operates on the principle of transmitting mechanical waves through the composite material with one transducer and receiving them with a second transducer. The transmitted wave can either be continuous or pulsed. The presence of a defect, such as a delamination or unbond condition, is indicated by a reduction in the magnitude of ultrasonic energy reaching the receiving transducer.

One of the advantages of the through-transmission methods is that a better near-surface resolution is obtained as a result of using transducers at separate locations for transmission and reception of the energy. This permits detection of defects just below the surface of the composite material. Attenuation is less of a problem with the through-transmission method, because the energy must travel only once through the material.

A disadvantage of the through-transmission method is the careful alignment required between transducers. Effects due to surface roughness, erratic couplant, and air bubble entrapment are doubled. Finally, no information regarding depth of flaws is available.

- o Reflector-Plate Immersion (RPI) Test Method is, in general, subject to the same advantages and disadvantages as the TTI technique. It is, however, particularly well suited for the inspection of relatively large panels where access to both sides of the panel is limited.

2.1.4 More Sophisticated Ultrasonic Techniques

The previous discussion of ultrasonic test techniques centered on methods of coupling, transmitting, and receiving ultrasonic energy into and out of the composite part. The methods previously discussed rely primarily upon an amplitude and/or time of occurrence measurement(s) for defect detection. In addition to these measurements there is a class of measurements more quantitative in nature and in specific areas of application that can be related to composite material properties and/or defect characterization. Their use, however, is not wide spread due, in part, to inherent difficulty of interpretation and errors caused by variations of extraneous geometric and material properties. This, therefore, places most of these measurements in the area of laboratory techniques which are discussed in a subsequent section. Since they are being used, in a limited sense, for production and in-service inspection, a brief description is presented here.

- o Ultrasonic Attenuation Losses in composites result from two separate mechanisms, dissipative hysteresis losses and scattering losses. The former is sensitive to matrix properties, such as degree of cure, modulus, and extent of plasticization. Scattering is related to the number and size of the discrete discontinuities within the composite; hence, scattering losses are sensitive to matrix micro-cracking, fiber content, fiber size, etc.
- o Phase Measurements - A predominate factor affecting the phase change encountered by a reflected wave is the acoustic impedance mismatch present at the reflector interface. In general, the greater this mismatch the greater the phase shift. For the case of an unbond (where the unbonded surfaces are separated by air) the resulting phase shift is significant. Unfortunately, for the case of a composite where fiber/matrix interfaces are constantly being encountered by the ultrasonic beam, phase changes caused by these interactions can mask those caused by unbonds.
- o Resonance Techniques seek to vibrate the transducer/specimen system at its resonant frequency. The instrumentation is constructed to sense the amplitude of this resonant frequency. Conditions such as weak bonds, porosity and delaminations, alter the amplitude of this

resonant frequency and are, therefore, detectable. As was the case with several of the previously mentioned techniques, this method is also subject to errors caused by geometry and material variations. Also, the changes in amplitude caused by weak bonds is too small to be reliably detected. This technique is evaluated, but past experience indicated only marginal potential for success for most "real-world" application using existing commercial equipment.

- o Air-Coupled Low Frequency Ultrasonics - As compared to liquid coupled ultrasonics, air-coupled ultrasonics employ much lower excitation frequencies, usually in the range of 25 kHz to 40 kHz. Although this type of ultrasonics is not as widely employed as liquid-coupled ultrasonics, several systems are currently in use for aerospace applications. These include the Shurtronics Harmonic Bond Tester, and the Automation Industries Sondicator. These systems operate in either a pulsed or continuous wave propagation mode using either air-coupled or point contact means of inducing ultrasound into the part.

The through-transmission inspection method is noncontacting with air only as a coupling between the search units and test parts. The transmitter search unit is positioned in line with and on the opposite side of the test part from the receiver search unit. The ultrasonic energy is transmitted through the part and received and monitored within the first 3 to 5 cycles for variations in signal phase and/or signal amplitude. The through-transmission noncontact method of inspection is generally used when each scan path is over an area of uniform part geometry. This method is particularly suited to inspection applications requiring high-speed, automatic scanning of the test parts.

In the point-contact inspection method the search unit is in contact with the test part, but no liquid couplant is required. The inspection is performed by placing the transmit and receive search units in direct contact with the test surfaces of the part. The transmit and receive search units may be positioned near each other on the same side of the test piece or directly in line with each other and on opposite sides of the test piece as described in the through-transmission test. Defect information is monitored in the same manner as

described for the through-transmission test. The contact method is best suited for a point by point inspection of parts having regular geometry. For continuous tests, rolling contact search units have been made that provide an accurate test.

For most applications the method is generally capable of detecting discontinuities 1/2 inch and larger. This limitation is basically due to the low operational frequency of the test and size of the search units used.

2.1.5 Thermal Methods

Thermal nondestructive testing methods are based upon the detection of thermal property variations in materials caused by the presence of flaws. Two methods for detection of thermal property variations in composites are thermographic methods and thermochromic methods. Thermographic methods normally employ scanning infrared sensors capable of making noncontacting surface temperature measurement. Thermochromic methods utilize temperature-sensitive liquid-crystal solutions or thermosensitive paints applied to the material surface to indicate temperature nonuniformities through color changes.

The application of thermographic and liquid-crystal methods to the non-destructive testing of composites is possible only if the flaws of interest (i.e., delaminations, voids, and foreign material inclusions) create significant thermal conductivity variations in the composite material. Detection of thermal conductivity variations can be accomplished by introducing heat flux into the material to produce a temperature perturbation at the surface.

- o Video Thermographic Inspection is basically an optical scanning system sensitive to radiation in the infrared region of the electromagnetic spectrum. The infrared radiation emitted from a surface is indicative of the surface temperature and emissivity; thus, for surfaces of relatively constant emissivity, the optical infrared scanning method can be a very effective means of monitoring surface temperature. Hence, the applicability of this type of infrared system is dependent upon two important characteristics; the defects of interest must cause sufficient thermal conductivity variations to be detected as surface temperature nonuniformities and the emissivity of the surface must be relatively constant to make accurate temperature readings possible.

- o Thermochromatic methods of surface temperature monitoring require that a uniform layer of the solution be applied to the test specimen surface. Variations in the surface temperature of the material cause distinct color changes in this layer covering the specimen. By monitoring the color of the layer, one can readily detect areas of nonuniform temperature. A permanent record is obtained by photographing the surface image.

2.1.6 Radiography

X-rays and gamma rays are very short wavelength radiation capable of penetrating and being differentially absorbed by solid material. It is the phenomena of differential absorption that causes an image to be formed on film at the back side of the specimen. Because radiography results in an image of the part and its associated discontinuities, it has been employed extensively in the aerospace and other industries. The sensitivity of this technique for flaw detection is a function of a number of test and material parameters. First, there must be significant differential absorption between the parent material and the defect. For the case of graphite/epoxy (G/Ep) this differential absorption is quite small as compared to metals. Hence, optimization of the other test parameters is necessary to obtain adequate sensitivity and resolution. Low energy x-rays (to 75 KV), ASTM Type I film and optimum time/milliampere and distance relationships are used to develop high contrast, high resolution radiographs. Radiographic information is catalogued and correlated with other NDI data and mechanical test data. Since film to source distance is in excess of 48 inches and film to object distance is less than 1.5 inches, geometric focus is not a problem. Control of the film processing eliminates film sensitivity problems. The two remaining items - technique and contrast can be controlled to assure maximum radiographic sensitivity. Alternate means of recording and interpreting the radiographic images are available. These include numerical and differential image analysis techniques. The radiographic technique is sensitive to mislocated details, cracks in thick laminates, and unbonds in vertical ties.

2.1.7 Penetrant

This method is very successfully used on metallic and some non-metallic structures to detect discontinuities open to the surface. However, existing systems have not been successfully used on composite materials. The method uses a chemical which fluoresces under ultraviolet light, suspended in a low viscosity solvent. The penetrant solution is applied, then the surface is lightly rinsed, dried, and viewed under a "black light". Surface discontinuities contain an accumulation of the fluorescing material and are visibly detectable. The general porousness of composite materials presents a difficulty in the use of this method. Also, surface coatings such as paint and lightning strike protection interfere with the process. In some instances, alcohol and similar materials have been used with some success on unprotected surfaces.

A penetrant system has been developed by the Air Force Materials Laboratory which indicates the presence of openings in composite/metal honeycomb and adhesively bonded components which would permit water entry and thus corrosion of these parts (1). The system depends on the addition of a chelating agent to a carrier fluid. The penetrant only becomes fluorescent when it contacts the metal substructure. This distinctive action allows the system to differentiate between flaws which permit water entry to the structure, and thus cause corrosion, and those that do not. The penetrant system also has application to any coated metal structure where defects in that coating must be detected.

2.2 LABORATORY NDI TECHNIQUES

The type of inspection to be utilized at NARF facilities does not allow the development of new and exploratory NDI techniques. But, to allow the maximum potential application of the data to be generated during the program, it is highly desirable that as many emerging NDI techniques as feasible be included. Some techniques that show promise for improved NDI of composites are the following ultrasonic scattering measurements, ultrasonic spectroscopy, quantitative ultrasonics, neutron radiography, neutron radiation gaging, vibro-thermography, acoustic holography, optical holography, eddy currents, microwaves, dielectrics, and ion graphing. Throughout the program other techniques are identified and interjected into the discussion where appropriate.

2.2.1 Ultrasonic Scattering Measurements

Since a predominate mechanism for composite damage development is matrix cracking leading to fiber/matrix debonding and ply delamination, it is extremely desirable to have a technique that would be capable of quantifying the extent of these types of damage. As an ultrasonic wave propagates through a composite specimen, both independent and coupled interactions occur. These interactions include attenuation (both scattering and dissipative losses), Bragg interference, and velocity perturbations. Associated with each of these ultrasonic wave interactions are characteristic properties (both geometric and material in nature) of the composite. Predominate among these interactions is the process by which the ultrasonic wave is scattered by the inherent fiber/matrix interface geometries and damage associated with matrix cracking. The functional form of these scattering interactions is highly dependent upon the wavelength to scatterer diameter ratio (λ/d), the scatterer to matrix acoustic impedance ratio, scatterer shape, scatter/matrix interface properties, and the incident angle of the ultrasonic wave. Among these factors, λ/d is of the greatest interest. This ratio not only affects the functional relationship of the scattering losses, but also the scattering profile. Hence, for this application, it should be possible to differentiate between scattering caused by the fiber geometry and that caused by matrix cracking.

Recent work has shown that ultrasonic attenuation and scattering measurements are particularly sensitive to matrix microcracking (2). Each microcrack increases the amount of ultrasonic energy loss by scattering hence also the total attenuation. Other investigators have studied the relationship between attenuation and composite damage (3) and found that a marked trend exists. Attenuation measurements, however, are usually difficult to quantify because their absolute value is affected by a number of test related factors, such as specimen geometry, couplant losses, transducer frequency and transducer efficiency. More recently, extension of classical scattering theory by Serabian, Williams, and Brown (1, 2, 4) has resulted in the definition of a new ultrasonic parameter, the "scattering factor". This parameter is a material constant and is measurable in a manner similar to ultrasonic attenuation, but is not affected by the extraneous parameters affecting attenuation measurements. Thus, quantitative correlation is now possible.

2.2.2 Ultrasonic Spectroscopy

Under certain conditions, an ultrasonic wave propagating through a composite undergoes perturbations in its frequency content as related to the geometric and material properties of the composite. The frequency content of a pulsed RF ultrasonic signal is determined by using a delayed linear gate to input the desired pulse to a spectrum analyzer for display. This display is the Fourier transform of the RF signal and is indicative of the relative values of the frequency components of the transformed pulse. A typical spectral display for a six ply G/Ep composite is shown in Figure 2.2. The x-axis scale of this figure is 1 MHz/div. with the center frequency being 5 MHz. A great number of factors effect the shape of this frequency spectrum, including testing practices, part geometry, ply configuration, and material property changes. The characteristic peaks and valleys are caused by Bragg diffraction (as a result of the laminated configuration). Peak frequency shifts can also be caused by composite velocity wave propagation changes.

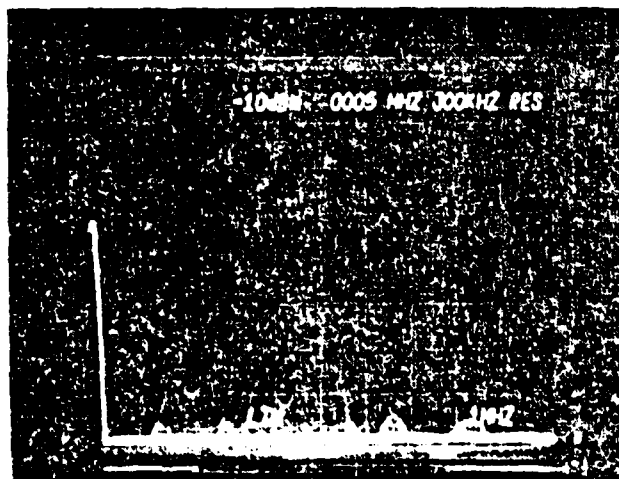


FIGURE 2.2 TYPICAL FREQUENCY SPECTRUM FOR A 6-PLY G/EP COMPOSITE USING A WIDE-BAND 5 MHz TRANSDUCER

2.2.3 Quantitative Ultrasonics

Quantitative Ultrasonics is a generic term used to indicate ultrasonic technology capable of defining flaw and/or material characteristics. For this discussion, it is used to mean the correlation of ultrasonics pulse "features" with defects in a composite material. A feature is taken to mean a mathematical shape function or transformation of the pulse that can be related to defect property change. These features are then combined in a unique manner to form a predictive equation that is the best estimator of the measured quantity (in this case composite damage). Considerable effort in these areas has been funded by AFML (5) and the results appear quite promising. Work is presently underway applying similar technology specifically designed for NDI applications, using an advanced data analysis scheme (6, 7). This technique, entitled Multivariable Analysis (MVA), employs sophisticated empirical and statistical data analysis algorithms to determine the best set of measurement parameters and combination of these measurement parameters to predict and quantify a certain desired material variable (in this case composite damage).

2.2.4 Neutron Radiography

Radiography with thermal neutrons has emerged in recent years as a viable NDI technique, providing a powerful complement to other techniques for many applications, and standing as the only technique for flaw detection in other instances. The technique has attained state-of-the-art status in several areas. In production pyrotechnics inspection, it has become mandatory for most devices. It is also a standard production technique for detection of residual core material in investment cast turbine blades (8). At Vought Corporation, neutron radiography is a required NDI procedure in production of a phenolic fiberglass to aluminum port cover assembly for the ramjet combustor in the Low Volume Ramjet Development Program under Naval Air Systems Command Contract No. N00019-68-C-0605. In-service inspection of aircraft for corrosion using neutron radiography has been demonstrated using Californium 252 as a neutron source (9, 10), and more recently, the technique has been demonstrated effective for adhesive bond inspection of aircraft wings (9, 11).

Increasing diversity of materials incorporated into current designs for advanced structures places more stringent requirements than before on radiographic and other techniques for nondestructive evaluation. Use of designs incorporating hybrids of composite and metallic components has resulted in significant gaps, previously non-existent, in ability to effectively inspect structures using conventional x-ray, ultrasonic, and other techniques. Small voids, cracks, porosity, and flaws in metal shim/composite panels, secondary bondlines, and complex close-out structures are examples of difficult NDI areas. Advanced state-of-the-art and applicable laboratory NDI techniques must be brought to bear on these structures to fill such gaps.

Due to fundamental differences in the interaction mechanism of neutrons with matter, as compared with x-rays, radiographic imaging with neutrons yields internal structural information which is for the most part complementary to that attainable with x-rays (12). Small thicknesses of low density materials containing significant amounts of hydrogen, such as epoxies and adhesives, for example, can be clearly imaged by thermal neutrons through substantial thicknesses of structural metals. Studies have shown that moderate-intensity neutron sources can be utilized in effective inspection of structures containing composites and adhesives (9, 13). Neutron techniques are capable of detecting with good resolution .020-inch adhesive voids in thick composite/metal specimens.

Neutron radiographic techniques are particularly suited to inspection of adhesive or epoxy specimens for determining the uniformity of thickness, in the case of adhesive layers, and the pattern or extent of matrix mixing in the case of epoxy composites. Air voids and many types of inclusions are readily imaged with the technique.

One of the chief advantages of neutron radiography over x-ray techniques is its ability in many instances to selectively penetrate materials of similar densities. In panels comprised of several different materials, flaws can easily be associated with the layers containing them. In addition, because of this characteristic, neutron radiographic NDI techniques are amenable to the inspection of many entire structural assemblies which were heretofore precluded to final-assembly inspections.

Neutron radiography is subject to some of the same limitations as those of x-radiography, viz., (1) fine cracks must be orientated parallel to the radiation beam; (2) access is required to both sides of the specimen; (3) sensitivity and resolution decrease with increasing thickness; and (4) radiation safety procedures must be strictly adhered to.

Although experimental data is available on the sensitivity of neutron radiography for detecting accumulated moisture in aluminum honeycomb structures (sensitivities of less than 10 microliters of water in typical honeycomb structure, Reference 14), application to detection of moisture in composites remains largely unexplored. It is to be expected that the technique is not as sensitive as for metal structures due to the substantial neutron absorption in the epoxy itself. However, the sensitivity of neutron inspection can be increased by utilizing neutron gauging techniques rather than film radiography in the case of homogeneous laminates such as found in many composite structures. This technique would involve a one-dimensional through-transmission measurement similar to that employed in gamma gauging.

It is anticipated that the most extensive application of neutron radiography is in the evaluation of the integrity of the composite, and to provide baseline data for flaw detection sensitivities and correlation of detected flaws with test results. The technique is useful for detection of accidental manufacturing flaws including porosity, resin rich or resin poor areas, resin flow into core, voids and inclusions in such specimens, as well as mislocated holes and certain types of cracks.

2.2.5 Neutron Radiation Gauging

A laboratory NDI technique with potential application in determining resin uniformity in "as-manufactured" composite test coupons is that of quantitative measurement of thermal neutron through-transmission by scintillators or other high-efficiency detectors, which provide a simple meter reading. This method, a radiation gauging technique (15), lends itself to determination of the volume fraction $V_{\text{epoxy}}/V_{\text{total}}$ of a graphite epoxy specimen, in as much as the predominant thermal neutron absorber in such a specimen is the epoxy. This is due to its substantial hydrogen content which is the dominant contributor to the linear absorption coefficient of the epoxy. In addition to its advantage in selective absorption and its greater sensitivity over film radiography, this technique has the advantage over other radiation gauging methods which use x-rays or gammas in that a fixed radiation energy which is universal from one laboratory to another ($\sim .025$ eV for thermal neutrons) is used. This characteristic allows for easier standardization and interpretation of NDI results. The capability of such a method as a scan system depends on the size of the collimator aperture, the scan speed, the neutron flux at the detector, the detector efficiency, and the linear absorption coefficient of the test coupon. It is expected from sensitivities reported for such systems (16) that detection of changes in epoxy volume fraction of 5% or less is attainable at scan speeds approximating 1 cm/sec. This laboratory technique should be evaluated to determine its detection sensitivities for application to NDI of composites.

2.2.6 Vibrothermography

This novel inspection technique, developed under AFOSR and AFML contracts, utilizes vibrational excitation of the composite part to generate localized heating in and around local flaws and discontinuities. These local variations in temperature are then detected using a scanning infrared video camera. To accentuate defect sensitivity and resolution a number of novel methods of vibrational excitation are employed. The originators of this technique have determined that it is possible to vary the nature of the excitation (the mechanical parameters as well as the excitation source) in such a way as to

selectively excite specific types of irregularities in composite materials, including G/Ep. In addition, since these new techniques do not require tensile loading of the specimens, they have the potential of being developed into a portable and flexible inspection technique.

2.2.7 Optical Holography

Holographic nondestructive testing entails the use of holographic interferometric methods to learn about the presence of subsurface inhomogeneities. An optical system, based upon a laser source of illumination, is used which records the light fields emanating from a test object and its interference with a second field which is simple in form and easily reproduced. The image of the original object can be reconstructed by illuminating the recording (usually on photographic film) with the original second field (denoted the reference field). Upon viewing the image through the film plate, the reconstruction is a remarkably good replica of the original object - so good in fact that if the original object is still in place during the illumination of the plate, and it is also illuminated, under normal conditions these two light fields tend to interact and interference fringes are observed. This phenomenon is called real-time holographic interferometry.

The significance of this effect is seen when a slight amount of stressing is introduced into the test piece. The stressing can be caused by thermal gradients, mechanical displacements, vacuum loading and vibrational excitation, among others. This stressing is observed in the holographic interferogram as a shift in the general contour of the observed fringes. The use of this technique in nondestructive testing becomes evident when the material under test responds in some nonuniform manner due to the stressing. Thus a material nonhomogeneity is detected by a local deviation in the general contours of the interferometric fringes.

Alternate methods of detecting this material inhomogeneity using holographic techniques are possible but are fundamentally limited by the characteristics of real-time holography. These are that the test part must be rigidly mounted during exposure (about one second for continuous lasers and about ten nanoseconds

for pulsed lasers) and not be moved until the film has been developed and replaced in its original test position. Systems have been devised which develop the film in place, and thus the test piece must remain immobile only for the duration of the film development. Flaw detection requires the observation of the holograms in a dimly-lit room by trained personnel and is not readily amenable to automatic processing.

Field applications of such systems have been in existence with varying degrees of success. Systems using the test piece itself as a source of the reference beam have relaxed the requirements of ultrastable test systems. The use of pulsed lasers has eliminated the need for stabilized test systems. Rugged installations have been designed which are useful in the noisy environments of industrial installations.

2.2.8 Acoustic Holography

The acoustical holographic technique may be useful for inspection of composites following fabrication. Both liquid surface and scanning techniques are available. The liquid surface technique uses two transducers driven by the same generator. Superposition of object and reference wavefronts on the liquid surface creates an interference pattern. The pattern is then detected and displayed optically. The scanning technique uses signals from a transducer in the pulse-echo mode. This signal is mixed with an electronically generated reference and the resultant signal is used to modulate a light beam. This beam is used to expose the holographic plate. Both techniques provide images of the internal structure of test specimens. Recording techniques are used to preserve the data. This technique is used to selectively test a group of specimens for comparisons with other more conventional techniques.

2.2.9 Eddy Current Methods

When a coil carrying alternating current is brought near a conducting material, eddy currents are induced in the material by electromagnetic induction. The magnitude and other characteristics of the induced eddy current depends upon the magnitude and frequency of alternating current; the electrical conductivity, magnetic permeability, and shape of the specimens; and the presence of discontinuities and inhomogenities in the specimen. The intensity of the eddy currents is greatest at the surface, falling off sharply in intensity with depth. The depth of penetration is highly frequency dependent, the higher frequencies having less penetration.

Eddy current testing has two potential applications for composites. Using lower frequencies (of the order of 50 KHz), eddy currents can be used to evaluate corrosion damage and other structural damage to aluminum honeycomb. Since graphite is a conductor, there is a potential for eddy current inspection of the G/Ep composite. The eddy current path is part resistive and part capacitive; the fibers being resistive and the gaps between the fiber filled with epoxy the capacitive part. Experiments have shown that eddy currents at relatively high frequencies (greater than 50 MHz) are sensitive to fiber volume fraction, fiber orientation, and cracks. Even at these high frequencies, the depth of penetration is greater than three millimeters.

2.2.10 Ion Graphing

This technique has primarily been used for monitoring the state of cure and detecting moisture content of polymer resins. Basically the technique is used to measure the current carrying capability of the sample and hence, indirectly, is a measure of volume resistivity. However, due to the fact that the conductivity of the polymer systems is usually quite low, extremely sensitive instrumentation is required to measure current flow. Further, the monitoring system must be adequately protected electrically to prevent data distortion from stray current flow.

The implementation of these techniques to the case of G/Ep adds an additional complication, in that variations in fiber density may cause resistivity variation of equal or greater magnitude than those due to the curing process or moisture absorption. Therefore, this technique is used selectively to monitor cure, moisture pickup, and fiber volume fraction variations.

2.2.11 Microwave Techniques

Microwaves are electromagnetic waves, the velocity and attenuation of which are dependent upon the properties of the medium through which they are propagating. Hence, they can be used to determine changes in material properties. Since the material properties that influence the microwaves are different from those that most strongly affect ultrasonic waves or x-rays, they cannot be directly compared. An important limitation to the use of microwaves, however, is their inability to penetrate deeply into electrical conductors.

Another limitation of microwaves is their comparatively low power of resolving localized anomalies. If a receiving antenna of practical size is used, an anomaly whose effective dimension is significantly smaller than the wavelength of the microwaves used cannot be resolved, i.e., distinguished as a separate, distinct flaw. At present, the shortest wavelengths for which practical microwave apparatus exist are of the order of several millimeters. Consequently, microwave testing is not presently suited where flaws are significantly smaller than 1 millimeter.

In spite of these limitations, microwaves have been used effectively in the inspection of fiberglass structures. They have been effective in finding areas of lack of cure as well as zones of excessive resin and regions of unbond. The amplitude of the reflected waves is most sensitive to variations in the resin structure of the fiberglass which affects the dielectric constant of the material. Information related to the thickness of the samples under test as well as their position is contained in the phase of the transmitted or reflected microwaves.

The prime limitation of utilizing microwaves for the inspection of G/Ep is that the composite is conductive. Its conductivity, although not as high as metals, is significantly higher than for the case of fiberglass. However, experimental measurements have shown that microwaves are capable of penetrating G/Ep. The signal intensity loss in transversing an 8-ply G/Ep composite is of the order of 70db. These losses, although high, are within the dynamic sensitivity of laboratory grade microwave equipment.

2.3 NDI MONITORING OF MECHANICAL TESTING

As previously stated, composites fail by the interaction and the eventual coalescence of several distinct damage mechanisms, including fiber breakage, matrix cracking and crazing, fiber/matrix debonding, and ply delamination. When these damage mechanisms coalesce and propagate, this phenomena is best quantitized as the propagation of a "damage zone". The characterization of this damage zone is substantially more difficult than for the case of metals where damage is usually in the form of initiation and propagation of a single crack. Hence, for metals relatively simple damage monitoring devices such as crack-opening-displacement (COD) gages, strain gages, and optical extensometers have proven to be sufficient. But these techniques alone are not adequate for

detecting and monitoring damage initiation and propagation in composites. Therefore, during the destructive testing of the composite specimens, a number of advanced real-time NDI techniques are employed. These techniques include time and spatially gated acoustic emission, infrared video thermography, x-ray opaque enhanced radiography, real-time ultrasonic attenuation and scattering measurements, brittle and photoelastic coatings, and neutron radiography.

A number of real-time NDI techniques have been shown to be quite sensitive to detecting and monitoring composite damage. Techniques that are based upon energy emission, such as acoustic emission and infrared thermography, have been used to detect and quantify composite damage in both polymer and metal matrix composite (17-70). Since these techniques are directly related to the energy released during the fracture process, they are ideally suited for relating the damage phenomena to degradation of composite structural integrity as measured by classical structural parameters.

2.3.1 Acoustic Emission

Acoustic emission techniques (AE) are based on the detection of low level sound emissions from a structure as it is subjected to external stresses. The emissions are caused by microscopic changes such as crack initiation and propagation, matrix crazing, fiber breakage, and fiber pullout. As the localized changes occur, energy release mechanisms include sound waves that radiate in all directions. The high frequency sound is detected by sensors which are attached to the structure's surface in selected arrays. Electrical signals from the sensors are amplified and processed to obtain data in various forms. The data can include count rate of emissions, total count of emissions, amplitude distribution, counts per event, and frequency content. Another data form is the relative time of arrival of burst emissions at the sensors. Using this data, along with the geometry of the structure and sensor array, the point of origin of the emissions can be calculated.

Acoustic emission techniques are used to monitor selected specimens during physical testing. The specimens monitored with AE are limited to those which contain no flaws or singular flaws, are static or fatigue tested to failure, and are not monitored with other NDI methods, such as brittle coating, which could generate false emissions.

Signal processing and data display includes, at a minimum, count rate, total count, amplitude distribution, and counts per event. Burst emissions are also analyzed for frequency content. Cross-correlation techniques are utilized to examine the AE data and corresponding failure processes. Subsequent specimens and test procedures can then be designed to further confirm the correlations.

2.3.2 Thermography

Time-resolved infrared video-thermography is used to detect and monitor damage initiation and propagation during cyclic fatigue tests (both spectrum and constant amplitude loading). As previously discussed, fatigue damage in composite materials can be monitored quantitatively by recording the heat images formed by the dissipative damage events as they occur during the fatigue test. The infrared thermovision system using an IR camera and color TV Monitor is sensitive to surface temperature differences on the order of 0.1 degrees centigrade. Energy dissipation associated with defects will be greater than the surrounding area, thus providing a slight temperature increase at the defect location. For thin plate specimens, then, the position of damage can be determined, and the amount of heat emitted is related to the severity of damage. Since the heat camera used is a video device, the method is also time-resolved and records data during the test. Also, since the heat produced by the specimen is monitored, the method is completely passive and does not interfere with the test itself or other data acquisition equipment used concomitantly. Hence, no special specimen preparation is required. This technique is used primarily as a method for recording the special distribution of damage during fatigue tests. Since the technique requires the heat generation associated with cyclic loading, little use is made of thermography during static tests.

2.3.3 X-Ray Opaque Enhanced Radiography

X-ray opaque enhanced microradiography has been shown to be extremely sensitive to fatigue, static and impact damage that is typified by matrix cracking and crazing and delamination. This technique uses a portable X-ray unit that has been specially modified to allow extremely low Kv exposure (as low as 1 Kv). These low energy exposures coupled with a very small focal spot tube make possible microradiography with up to 100X magnification. Hence, using these microradiographic capabilities and an X-ray opaque penetrant to penetrate

and enhance the damage an extremely detailed "picture" of the composite damage can be obtained. It should be noted that using conventional radiographic techniques and/or visual techniques this damage is not detectable.

The procedure for this technique is as follows. Intermediate during the loading of the test specimen (while in place in the testing apparatus) Tetra-bromoethane (TBE) or other X-ray opaque liquid is applied to the surface of the test specimen, allowed to soak for 15 seconds, and then wiped off. Using a portable, specially modified low Kv x-ray unit, a radiograph is taken with the specimen in place. Successive exposures at incremental loadings will provide a time-resolved record of damage development. Radiographs taken in this manner with small grain film can be magnified up to 100X. Should high speed, stop action radiographs be desired, "flash radiography" may be employed. This technique, although having less resolution, is capable of fraction of second exposure times. For short term tests, the TBE is allowed to remain on and in the specimen. Previous applications of this technique have shown TBE to have little degradation effects upon the composite performance. However, the long-term effects (during a creep test) of TBE upon composite performance is yet unknown. Therefore, several control tests are performed to determine its effect prior to its application to these types of tests.

2.3.4 Ultrasonic Methods

Several ultrasonic techniques have been evaluated for use in monitoring fatigue damage propagation. Ultrasonic through-transmission has been successfully used to detect composite delamination. This technique requires unobstructed access to both sides of the test specimen. Ultrasonic through-transmission attenuation measurements have been successfully used to assess the level of porosity in composites. This technique is applicable for assessing microcracking produced during fatigue testing. When only one side of a specimen is unobstructed, ultrasonic pulse-echo techniques must be applied. Pulse-echo ringing techniques have been applied to detection of subsurface delamination and lack of bond. These ultrasonic contact tests require fatigue testing to be stopped for a short time.

2.3.5 Brittle and Photoelastic Coatings

The term brittle coatings is used to describe coatings which will fail or crack when a certain value of tensile stress is exceeded without an appreciable yielding or inelastic action preceding the actual cracking. If a composite structure coated with such a brittle material is subjected to loads, the initiation of cracks in the coating can be related to the tensile stress in the structure. The proper use of brittle coatings will then graphically show the distribution, magnitude, direction, and gradient of stresses on the actual structure. Surface and/or subsurface defects cause a perturbation in the stress field, and therefore, are detectable using brittle coatings during a static test. This process is, however, irreversible and is only sensitive to defects whose associated stress concentration is at or near the stress failure of the coating.

Photoelastic coatings are used in the same manner as brittle coatings, to determine surface stress distribution, magnitude, direction and gradient. The physical phenomena is, however, different and the display process reversible making continuous monitoring feasible. The procedure involves coating the specimen with a thin coating of photoelastic material backed with a reflective coating. The part is then loaded and illuminated with polarized light. The reflected light is then viewed through a polariscope and the fringe patterns analyzed using traditional photoelastic techniques to determine the stress state at the specimen surface. Defects would then cause perturbations in the surface stress state. This technique is directly applicable for the case of static test, but would require that fatigue tests be stopped periodically to take measurements. Also, any severe amounts of surface damage and/or permanent deformation would effect the accuracy of this technique.

3.0 STRUCTURAL ASPECTS OF SURVEY

To determine what questions to include in the survey, a general review of the industry was conducted examining types of construction, types of damage, and types of repairs currently in use, in development, and in proposal.

There are two basic types of construction currently in use on production aircraft. The first is aluminum honeycomb core bonded to either aluminum or monolithic composite laminate skins. This type of construction began as early as the late 1950's and is seen on aircraft such as the F-4, T-38, A-7, F-8 and

others. Currently, McDonnell is using graphite/epoxy skins over aluminum honeycomb on the F-15, F-18 and Y/AV-8B. Non-metallic core is not as popular, but is in use in proposal and developmental work.

The second type of basic construction is laminated skins. Boron/epoxy is used on F-14 and F-15 control surfaces and graphite/epoxy on F-15 speed brake, F-16 control surfaces, and the entire Y/AV-8B wing. Kevlar/epoxy, while not yet in wide aircraft use, is already in commercial use on boats and other areas replacing fiberglass. It is currently in use on the Lamps MK III helicopter and on the L 1011.

Thus it can be seen that the types of construction listed in the survey, particularly on page one, easily represent the common areas of experience of many of the aircraft companies in the U. S. It is from these common areas of production and development as documented by aircraft and report, from which the types listed are derived.

The damage types listed are the result of manufacturing, shop, and in-service experience through the industry. The worst types structurally are those which damage the fibers of a laminate, such as cracks, splintering, holes and such, ballistic damage, and erosion, since the fibers carry the majority of the load. The matrix associated problems, such as delamination, debond, porosity, moisture, impact, heat and resin softening, while not as serious as fiber damage are still of structural concern since the matrix transfers load between fibers and stabilizes the fibers in compression. Some "minor" damages such as "small" amounts of porosity can be tolerated but "minor" and "small" need to be more accurately defined. Matrix problems are also the most frequently encountered type of damage. Core associated problems are also of structural concern since the core carries shear loads and stabilizes the skins. Crushed core, node separation, and split core are also typical of problems already encountered in service of aircraft. Many of these problems occur in varying degrees of seriousness and guidelines need to be formulated which will correlate the seriousness of damage with the necessity for and type of repair to be used.

The purpose of a repair is to restore the damaged structure to its original form in as many ways as possible. While many repair methods have been proposed, most are still under evaluation and study. Some repairs, such as hot resin injection or resin coating, do their job well on matrix problems. Core repairs are relatively refined because of longer experience. The more serious damages, particularly ballistic laminate damage still require case-by-case investigation before they will be able to provide a total repair to the laminate in all structural areas (i.e. strength, fatigue, etc.) as well as in aerodynamics, corrosion and others. The most popular repair at present is the bolted/bonded external patch. While this will work structurally, it is aerodynamically unpleasant. Refinement and experience are necessary before fully adequate repairs of many composite materials are realized. Indeed many materials systems are only beginning to be understood in terms of original usage as well as in repair of these materials.

Thus, the questions contained in the survey represent the general experience of the aerospace industry and are biased by present usage and present developmental work. As new structural composite materials are identified and new uses for old materials are identified, this type of survey will have to be redone to encompass them. However, the information gained here will provide valuable insights to present as well as near future inspection and repair of current aerospace grade composite materials.

4.0 DATA CORRELATION METHODS

The data from the survey was copied onto paper tape files in a prescribed format. The data processing software then read these files and built the output from the distribution of responses to each question. The result was displayed in bar charts showing the number of affirmative responses in all modes for each question.

Before any work had begun, a coding form was designed which would facilitate the transfer of the data from the questionnaire to the computer with the least chance of distortion. Once the questionnaire had arrived the data was transcribed to the coding forms. The data was then checked for transfer errors. This information was then keypunched on to paper tape files. Each file, representing one questionnaire's responses, was then listed by the computer and verified.

The hardware environment that the processing was done in was hosted by a Hewlett-Packard 2100S Minicomputer. Peripheral devices included a teletype, paper tape punch, and high speed tape reader. The software processing environment consisted of an analyzer module (a Fortran II program) which would read N paper tape files and add its responses to distributions for each entry in a master file. When all data files had been read, then the master file was punched which contained the response distributions for the ensemble of questionnaire responses. The display module then read the master file and plotted the distribution for each file item.

5.0 DISCUSSION OF SURVEY RESULTS

5.1 CONFIGURATION OR CONSTRUCTION - QUESTIONS 1-3

Structurally, the survey responses indicate that while it is necessary to have the capability to inspect all types of composite structures, graphite/epoxy seems to be the most important or frequently encountered. Boron/Epoxv and Kevlar/Epoxv tied for second with the rest following in the same order as presented, for the laminated group. The reason for this stacking is probably based on cost vs. mechanical properties. Although Boron is stronger and stiffer than graphite it is two to three times as expensive. Kevlar is only slightly cheaper than graphite but about half as stiff. Densities are approximately .073, .058, and .050 for Boron/Epoxv, Graphite/Epoxv, and Kevlar/Epoxv, respectively. These coupled with the fact that graphite is coming down in cost, means that graphite is a highly attractive material and will be frequently encountered on aircraft. The other materials are not as far developed and more expensive, in general, than these first three. Both sandwich types rated very high on need to inspect with the metal honeycomb core rating slightly higher in importance. This is probably due to the fact that metallic honeycomb has a higher strength to weight ratio and a lower cost than non-metallic core at present and will probably be used more than non-metallic core.

Of the bonded types, the metal honeycomb/metal faces is rated as the most important, although all types are required to be inspected, probably because this type is in such frequent use today. Also well noted was composite with metal inserts and shims.

In summary, the survey indicated that all forms of advanced composites on aircraft need to be inspected and therefore the NARF's should possess the capability to do so. A summary of the ranking of importance of configuration is shown in Table 5.1. Clearly graphite/epoxy laminates are the most important and are already in heavy use on many Navy aircraft programs: F-14, F-18, S-3A, and V/AV-8B. Honeycomb sandwich structures are also in heavy use at present and will continue to be, with varying types of skin, and are thus second in importance. All the other materials or material combinations mentioned are in light use or developmental stages. These materials will be used in the future, possibly heavily, and the capability to inspect them should be acquired now so as to be prepared for their introduction on future aircraft.

TABLE 5.1

RESULTS - RANKING OF CONFIGURATION/CONSTRUCTION

1. BONDED METAL HONEYCOMB/METAL FACES
2. GRAPHITE/EPOXY LAMINATE
3. SANDWICH - METALLIC HONEYCOMB/COMPOSITE FACES
4. SANDWICH - NON-METALLIC HONEYCOMB/COMPOSITE FACES
5. BORON/EPOXY LAMINATE
6. KEVLAR/EPOXY LAMINATE
7. BONDED COMPOSITE WITH METALLIC INSERTS OR SHIMS
8. LAMINATED METAL/COMPOSITE MULTILAYER
9. HYBRIDS

5.2 DESIRABLE, PRIMARY, OR MINIMUM TECHNIQUES - QUESTIONS 4-6

Questions 4 through 6 were designed to get a consensus concerning which of the many available NDI techniques the NARF should be trained and equipped to perform. The responders were asked to specify which of the techniques listed (see p. 3 of questionnaire) would form a bare minimum repertoire for the NARF. Five techniques were most frequently identified as minimum repertoire for the NARF: Visual or Optical, Ultrasonic Pulse Echo, Penetrant, Tap Testing, and X-ray. Visual or optical and ultrasonic pulse echo ranked equally in receiving the highest number of responses followed closely by Penetrant and Tap Testing (see Figure 5.2.1). X-ray also ranked high in the number of responses received. An error in the questionnaire which listed C-scan and thru transmission as separate techniques may have been confusing to responders. The number of responses received for these techniques were combined to avoid misinterpretation of the results into a single category shown in all the figures and tables as ultrasonic through-transmission (USTT).

The survey also asked for an opinion as to which NDI techniques were not absolutely essential to the NARF, but which the NARF should be equipped to perform. These techniques were labelled as "desirable". Figure 5.2.2 summarizes the responses given to this question. Ten techniques were listed as desirable by more than half the responders: USTT, X-ray, Visual/Optical, Ultrasonic Pulse Echo, Penetrant, Tap Testing, Eddy Current, Eddy sonic, Low Frequency Air Coupled, and Sonic resonator. Therefore, to the list of six techniques originally indicated as minimum requirements, Eddy current, Eddy sonic, Low Frequency Air Coupled, and Sonic resonator may be added as desirable.

The techniques which did not appear to be considered desirable, as shown by the low number of responses (less than 25% of responders) included Thermography, Microwave, Ion graphing, and Holography (Acoustic). Borderline techniques (between 25% and 50% of responders) included Neutron Radiography, Thermochromatic Coatings, Acoustic Emission, Optical Holography, and Dielectric.

As part of this group of questions, responders were also asked to indicate which of the listed NDI techniques they would recommend as the primary inspection procedure to be most generally used. The techniques which were indicated frequently were Ultrasonic Through-Transmission, Ultrasonic Pulse Echo, and

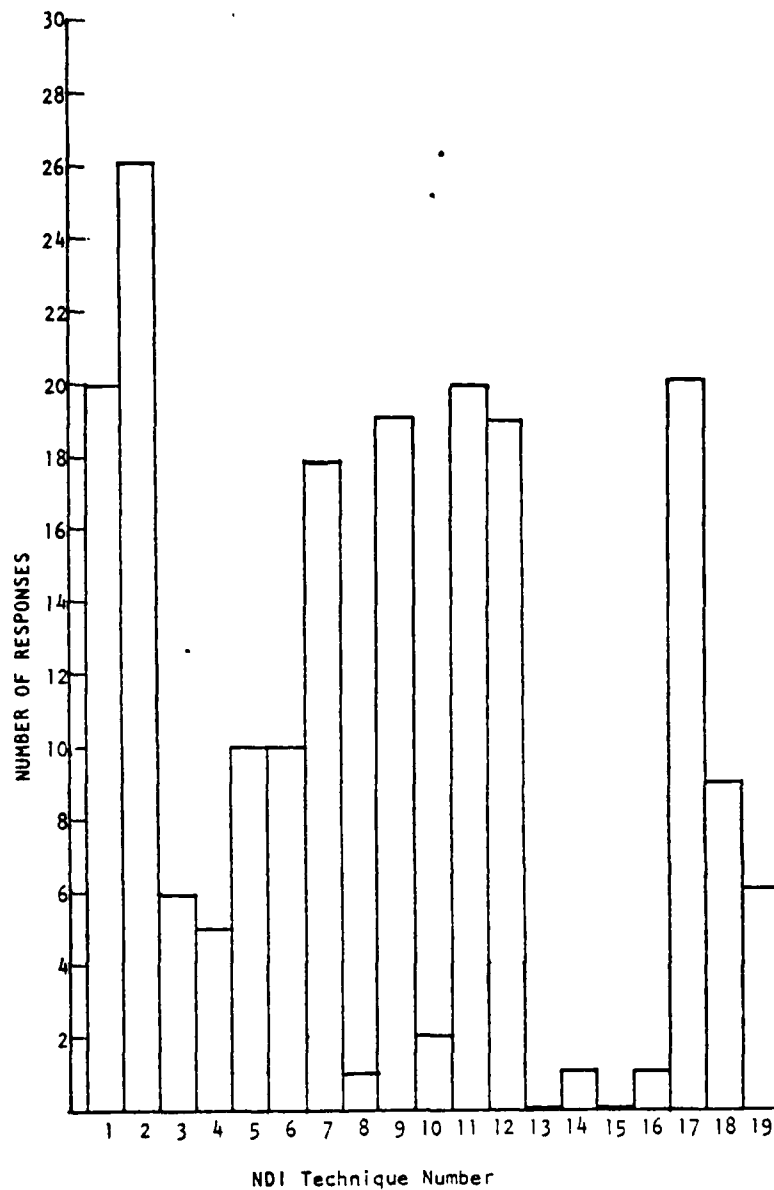


FIGURE 5.2.1 MINIMUM NDI TECHNIQUES
GROUPS OF TECHNIQUES FORMING A BARE MINIMUM REPERTOIRE

- | | |
|------------------------------|-----------------------------------|
| 1. Ultrasonic Pulse Echo | 11. Visual or Optical |
| 2. Thru-Transmission | 12. Tap Testing |
| 3. Sonic Resonator | 13. Thermography (Video or Vibro) |
| 4. Low Frequency Air Coupled | 14. Holography (Optical) Laser |
| 5. Eddy Sonic | 15. Acoustic Emission |
| 6. Eddy Current | 16. Microwave |
| 7. X-Ray | 17. Dielectric |
| 8. Neutron Radiography | 18. Ion Graphing |
| 9. Penetrant | 19. Holography (Acoustic) |
| 10. Thermochromatic Coatings | |

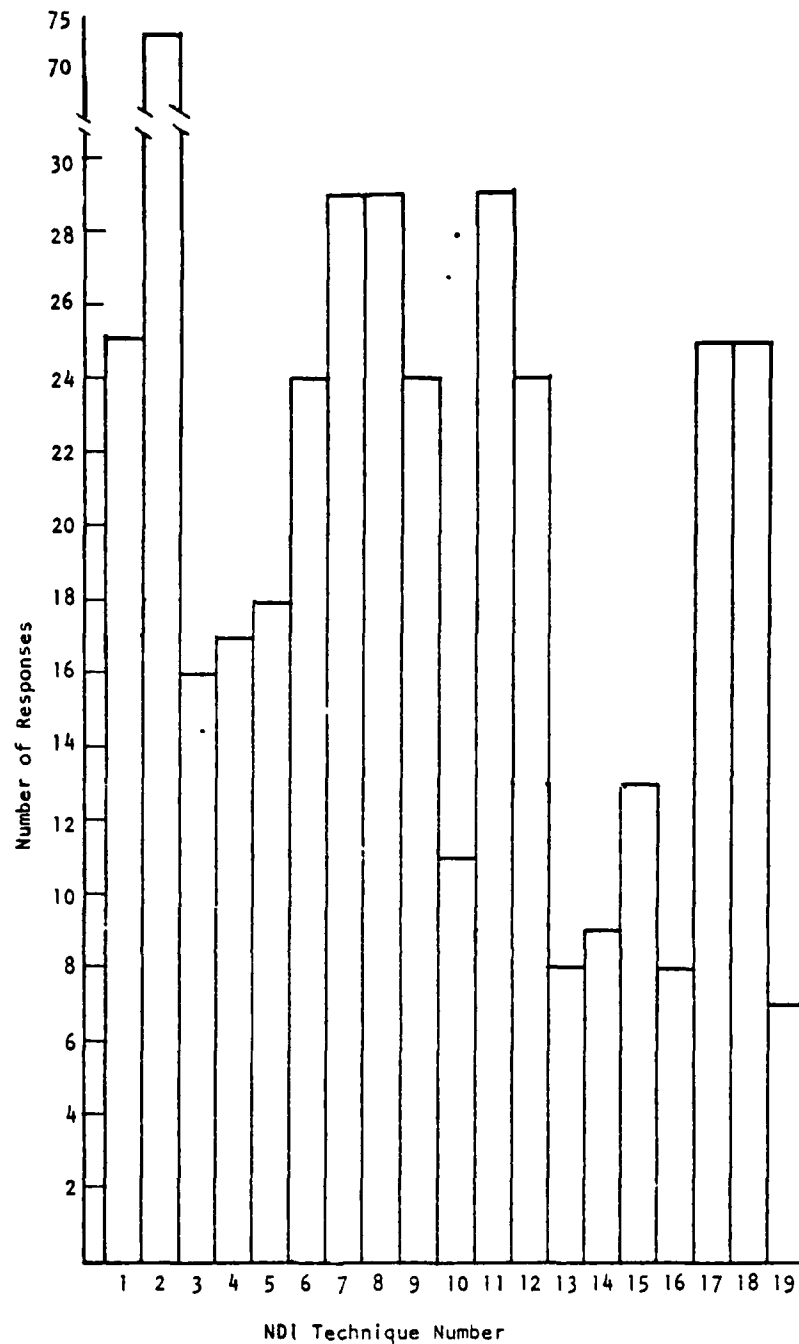


FIGURE 5.2.2 DESIRABLE NDI TECHNIQUES
NOT ABSOLUTELY ESSENTIAL, BUT SHOULD BE EQUIPPED TO PERFORM

- | | |
|------------------------------|-----------------------------------|
| 1. Ultrasonic Pulse Echo | 11. Visual or Optical |
| 2. Thru-Transmission | 12. Tap Testing |
| 3. Sonic Resonator | 13. Thermography (Video or Vibro) |
| 4. Low Frequency Air Coupled | 14. Holography (Optical) Laser |
| 5. Eddy Sonic | 15. Acoustic Emission |
| 6. Eddy Current | 16. Microwave |
| 7. X-Ray | 17. Dielectric |
| 8. Neutron Radiography | 18. Ion Graphing |
| 9. Penetrant | 19. Holography (Acoustic) |
| 10. Thermochromatic Coatings | |

Visual or Optical. X-ray, Penetrant, and Tap Testing also were noted in 25% or more of the responses. Figure 5.2.3 summarizes the responses concerning primary techniques.

5.3 RECOMMENDED TECHNIQUES FOR SPECIFIC CONFIGURATIONS HAVING SPECIFIC DAMAGE - QUESTION 7

Participants in the survey were asked to fill in a matrix by indicating the primary and back-up techniques recommended for inspecting the configurations shown in the matrix for the types of damage also specified in the matrix. The types of damage were defined in Table III, P. 5 of the questionnaire so that there would be no confusion because of differences in terminology. The definitions used are standard usages in the composites literature, although many people often use some of the terms interchangeably, e.g., debond, delamination, void.

Results from Question 7 are presented in Tables 5.3.1 through 5.3.14, according to damage type. Respondors left a large number of blanks in the matrix, making the results difficult to interpret. A blank could mean that there is not a technique available to satisfactorily perform the inspection in question or could indicate a lack of experience with the configuration to be inspected. Another possible interpretation is that the time involved in filling in the matrix was greater than the responder was willing or had available to spend. However, with these observations in mind, the responses still express a consensus, whether it is statistically valid or not. The tables list the two techniques receiving the most responses in each category. Tables 5.3.15 and 5.3.16 summarize the results for laminate and honeycomb configurations, respectively.

5.4 TECHNIQUES FOR INSPECTING REPAIRS - QUESTION 8

This question asked for a recommendation for techniques to inspect particular types of repairs that have been performed. A brief definition or description of the repair was given to try to avoid semantic difficulties. Table 5.4.1 presents a tabulation of the two most frequently specified techniques for primary and back-up use in inspection of the various repair types. Only five techniques appeared in the responses: X-ray, Visual, Tap test, Pulse echo,

and Through-Transmission. Overall, the preferred primary techniques were Visual, Pulse echo, and Through-Transmission, while Visual, Through-Transmission, and Tap test were the most frequently specified back-up techniques.

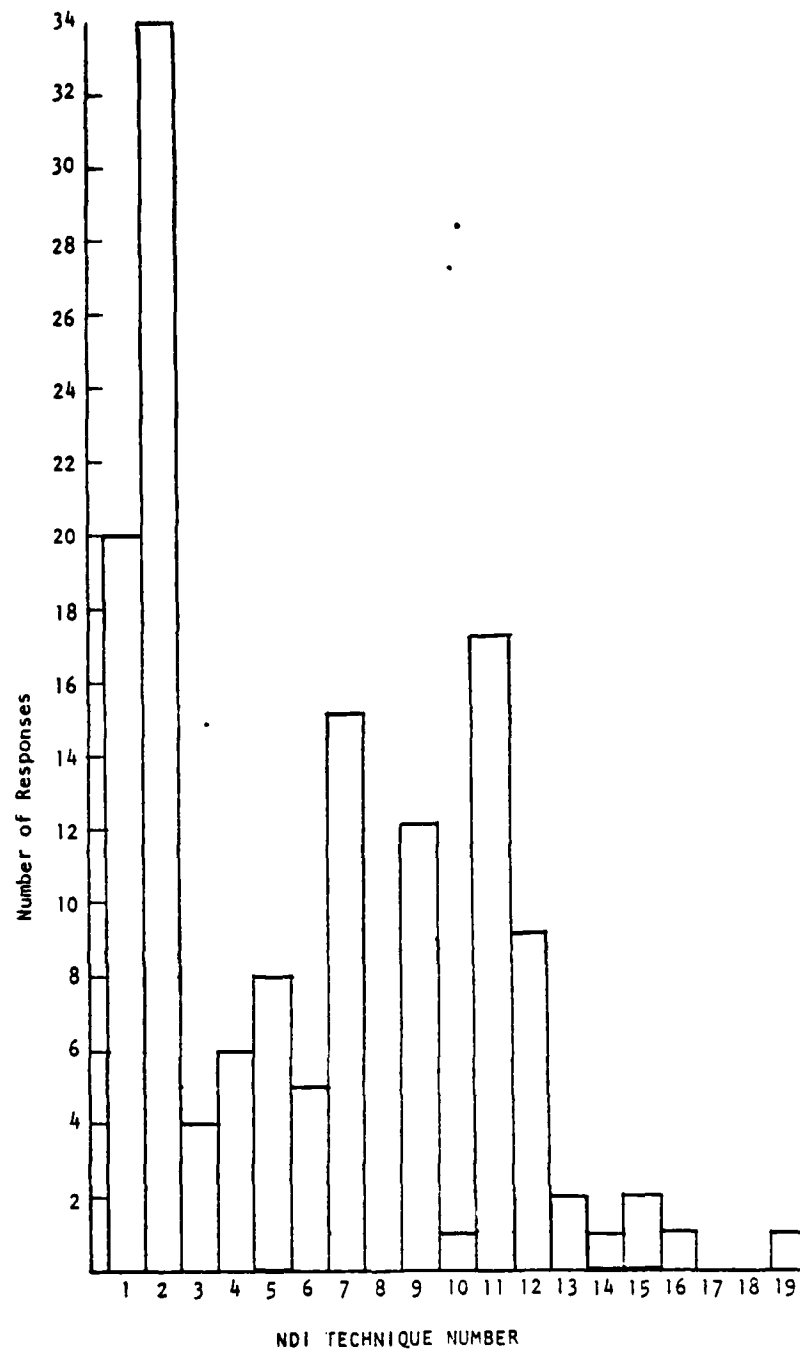


FIGURE 5.2.3 PRIMARY NDI TECHNIQUES
TECHNIQUE MOST GENERALLY USED

- | | |
|------------------------------|-----------------------------------|
| 1. Ultrasonic Pulse Echo | 11. Visual or Optical |
| 2. Thru-Transmission | 12. Tap Testing |
| 3. Sonic Resonator | 13. Thermography (Video or Vibro) |
| 4. Low Frequency Air Coupled | 14. Holography (Optical) Laser |
| 5. Eddy Sonic | 15. Acoustic Emission |
| 6. Eddy Current | 16. Microwave |
| 7. X-Ray | 17. Dielectric |
| 8. Neutron Radiography | 18. Ion Graphing |
| 9. Penetrant | 19. Holography (Acoustic) |
| 10. Thermochromatic Coatings | |

TABLE 5.3.1

DELAMINATION

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Thru-transmission Pulse Echo	Thru-transmission Pulse echo Sonic Resonator
Laminate/Laminate	Thru-transmission Pulse echo	Thru-transmission Pulse echo
Laminate/Metal	Thru-transmission Pulse echo	Pulse echo Thru-transmission Sonic Resonator
Metal H/C Core*	Pulse echo Thru-transmission	Thru transmission Tap Test
Non-Metal H/C Core*	Thru-transmission Pulse echo	Thru-transmission Pulse echo Tap test

* Delamination face sheet only

TABLE 5.3.2

DEBOND

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Thru-transmission Pulse echo	Thru-transmission Pulse echo Sonic resonator
Laminate/Laminate	Thru-transmission Pulse echo	Thru-transmission Pulse echo
Laminate/Metal	Thru-transmission Pulse echo	Pulse echo Thru-transmission
Metal H/C Core*	Pulse echo Thru-transmission	Thru-transmission Tap test
Non-Metal H/C Core*	Pulse echo Thru transmission	Thru-transmission Tap Test

* Debond-face to core

POROSITY

TABLE 5.3.3

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Thru-transmission X-ray	Thru transmission
Laminate/Laminate	X-ray Thru-transmission	Thru transmission X-ray
Laminate/Metal	Thru-transmission X-ray	X-ray, Thru transmission

TABLE 5.3.4

VERTICAL BOND VOID

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	X-ray	Pulse echo Tap test Thru-transmission
Laminate/Laminate	X-ray	Pulse echo Thru transmission
Laminate/Metal	X-ray	Thru transmission
Metal H/C Core	X-ray	X-ray Pulse echo Thru-transmission
Non-metal H/C Core	X-ray	Thru-transmission

TABLE 5.3.5

CRACKS

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	X-ray Penetrant, Visual	Penetrant, Visual X-ray
Laminate/Laminate	X-ray, Visual, Penetrant, Thru-transmission	Penetrant, X-ray Pulse echo
Laminate/Metal	X-ray Thru-transmission	Penetrant X-ray

TABLE 5.3.6

SPLINTERING

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual Penetrant	Visual Penetrant
Laminate/Laminate	Visual X-ray, Penetrant	Penetrant Visual
Laminate/Metal	Visual X-ray	Penetrant Visual

MOISTURE ABSORPTION

TABLE 5.3.7

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Thru transmission Dielectric	X-ray, Microwave
Laminate/Laminate	Dielectric Thru transmission	Microwave, Dielectric
Laminate/Metal	X-ray, Dielectric Thru transmission	Microwave, Dielectric
Metal H/C	X-ray N-ray	N-ray X-ray, Acoustic Emission
Non-Metal H/C	X-ray N-ray	X-ray, N-ray, Acoustic Emission

TABLE 5.3.8

IMPACT DAMAGE

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual X-ray	X-ray Pulse echo
Laminate/Laminate	Visual X-ray, Pulse echo	X-ray Pulse echo, visual
Laminate/Metal	Visual X-ray	Pulse echo Thru-transmission X-ray
Metal H/C	Visual X-ray Thru-transmission	X-ray Visual Thru-transmission
Non-Metal H/C	Visual X-ray	X-ray Visual

TABLE 5.3.9

BALLISTIC DAMAGE

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual X-ray	X-ray Pulse echo
Laminate/Laminate	Visual X-ray	X-ray Pulse echo
Laminate/Metal	Visual X-ray	X-ray Pulse echo

TABLE 5.3.10

FIRE OR HEAT DAMAGE

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual X-ray, Pulse echo	Visual Thru-transmission
Laminate/Laminate	Visual Pulse echo	Visual Thru-transmission
Laminate/Metal	Visual Eddy Current	Visual Eddy Current
Metal H/C	Visual Eddy Current, X-ray	Visual Eddy Sonic, Pulse Echo Thru-transmission
Non-Metal H/C	Visual X-ray	Visual Thru-transmission

TABLE 5.3.11

RESIN SOFTENING

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual Dielectric	Tap testing
Laminate/Laminate	Visual	Tap testing
Laminate/Metal	Visual	Tap testing

TABLE 5.3.12

EROSION

CONFIGURATION	PRIMARY	BACK-UP
Solid Laminate	Visual	X-ray
Laminate/Laminate	Visual	X-ray
Laminate/Metal	Visual	X-ray

CORE DAMAGE

TABLE 5.3.13

CONFIGURATION	PRIMARY	BACK-UP
Metal H/C	X-ray	Thru transmission
Non-Metal H/C	X-ray	Thru transmission

TABLE 5.3.14

CORE CORROSION

CONFIGURATION	PRIMARY	BACK-UP
Metal H/C	X-ray Eddy sonic	X-ray
Non-Metal H/C	X-ray	Acoustic emission

TABLE 5.3.15

CONFIGURATIONS CONTAINING LAMINATES,
LAMINATE-LAMINATE BONDS AND/OR LAMINATE-METAL BOND
TYPE OF CONSTRUCTION

DAMAGE TYPE	SOLID LAMINATE				BONDED			
	PRIMARY	BACK-UP	PRIMARY	BACK-UP	LAMINATE TO LAMINATE	PRIMARY	BACK-UP	LAMINATE TO METAL
DELAMINATION	USTT	USPE	USTT	USPE	USTT	USTT	USPE	USTT
DEBOND	USTT	USPE	USTT	USPE	USTT	USTT	USPE	USTT
POROSITY	USTT	X-RAY	X-RAY USTT	USTT X-RAY	X-RAY USTT	USTT X-RAY	USTT X-RAY	X-RAY USTT
VERTICAL BOND VOID	X-RAY	USPE	X-RAY	USPE	X-RAY	X-RAY	USPE	USTT
CRACKS	X-RAY	PENETRANT VISUAL	X-RAY VISUAL	PENETRANT VISUAL	X-RAY VISUAL	X-RAY USTT	PENETRANT USPE	PENETRANT
SPLINTERING	VISUAL	PENETRANT	VISUAL X-RAY	PENETRANT	VISUAL X-RAY	VISUAL X-RAY	PENETRANT	PENETRANT
MOISTURE ABSORPTION	USTT DIELECTRIC	X-RAY MICROWAVE	DIELECTRIC USTT	MICROWAVE DIELECTRIC	DIELECTRIC USTT	X-RAY DIELECTRIC	MICROWAVE DIELECTRIC	MICROWAVE DIELECTRIC
IMPACT DAMAGE	VISUAL	X-RAY USPE	VISUAL	X-RAY USPE	VISUAL	VISUAL X-RAY	USPE USTT	USPE USTT
BALLISTIC DAMAGE	VISUAL	X-RAY USPE	VISUAL	X-RAY USPE	VISUAL	VISUAL	X-RAY USPE	X-RAY USPE
FIRE OR HEAT DAMAGE	VISUAL	X-RAY USPE	VISUAL	X-RAY USPE	VISUAL	VISUAL	USPE USTT	EC
RESIN SOFTENING	VISUAL DIELECTRIC	TAP TEST	VISUAL	TAP TEST	VISUAL	VISUAL	TAP TEST	TAP TEST
EROSION	VISUAL	X-RAY	VISUAL	X-RAY	VISUAL	VISUAL	X-RAY	X-RAY

USTT - ULTRASONIC THROUGH TRANSMISSION
USPE - ULTRASONIC PULSE ECHO
EC - EDDY CURRENT

TABLE 5.3.16

CONFIGURATIONS CONTAINING HONEYCOMB CORE

DAMAGE TYPE	METAL H/C CORE		NON-METAL H/C CORE	
	PRIMARY	BACK-UP	PRIMARY	BACK-UP
DELAMINATION FACE SHEET ONLY	USPE	USTT TAP TEST	USTT	USPE TAP TEST
DEBOND, FACE TO CORE	USPE	USTT TAP TEST	USPE	USTT TAP TEST
CORE DAMAGE (CRUSHED, NODE SEPARATION, SPLIT)	X-RAY	USTT	X-RAY	USTT
CORE CORROSION	X-RAY	ES	X-RAY	AE
MOISTURE IN CORE	X-RAY	N-RAY ACOUSTIC EMISSION	X-RAY	N-RAY ACOUSTIC EMISSION
VERTICAL BOND VOID	X-RAY	USPE	X-RAY	USTT
IMPACT DAMAGE	VISUAL	X-RAY, USTT	VISUAL	X-RAY
FIRE OR HEAT DAMAGE	VISUAL	EC, X-RAY, USPE	VISUAL	X-RAY, USTT

USTT - ULTRASONIC THROUGH TRANSMISSION

USPE - ULTRASONIC PULSE ECHO

EC - EDDY CURRENT

ES - EDDY SONIC

AE - ACOUSTIC EMISSION

TABLE 5.4.1
RESULTS - REPAIR VERIFICATION

TYPE OF REPAIR	PRIMARY	BACK-UP
SURFACE REPAIR	VISUAL	-
LAMINATE REPAIR	USTT, USPE	USPE, USTT
EXTERNAL PATCH - Ti/FG	USPE	VISUAL, TAP TEST
EXTERNAL PATCH - G/E	USPE, USTT	VISUAL, TAP TEST
EXTERNAL PATCH - P/E	USPE, USTT	VISUAL, TAP TEST
EXTERNAL PATCH - BOLTED Ti	VISUAL	-
CORE REPAIR - CORE PLUG	X-RAY	USTT
CORE REPAIR - FILLER	Y-RAY	USTT
LIGHTENING STRIKE OR STATIC PROTECTION REPAIR	VISUAL	

5.5 COUPLANT FOR ULTRASONIC CONTACT METHODS - QUESTION 9

Question 9 in the survey asked the responder to discuss what couplant is preferred for ultrasonic contact methods and why. Table 5.5.1 lists the couplants suggested and the number of responses each received.

TABLE 5.5.1
ULTRASONIC COUPLING MEDIA

<u>COUPLANT</u>	<u>NO. OF RESPONSES</u>
Water	8
Water Soluble Colloid	8
Glycerin	5
Light Oil	4
Penetrant Emulsifier	2
30 Wt. Oil	2
Lithium Grease	1
Stopcock Grease	1
Petroleum Jelly	1
Water Soluble Machining Oil	1
Fokker Bondtest Fluid	1
Thixotropic Paste	1
No Response	5

A majority of those responding to the questionnaire (approximately 63%) preferred water or a water soluble coupling agent. Plain water and water soluble colloids such as Ultragel, Sonogel, Echogel, or Natrasol led the field. The reasons given for these preferences include economy, ease of clean up, and noncontamination of surfaces to which a repair bond may have to be made. The last reason is one of significance since complete removal of oil, grease, or silicon containing substances from an ordinary, much less a damaged surface, is essential for a good bond to that surface.

6.0 COMPILATION OF SURVEY FINDINGS

The conclusions which may be drawn from the NDI survey conducted as a basis for this report are limited as with any questionnaire. The instrument failed to highlight some areas and focused in too tightly on others. However, the general conclusions which may be drawn are:

- 1) Graphite/epoxy solid laminates, metal honeycomb with metal faces, and metal honeycomb with composite faces are considered to be the most frequently encountered types of constructions.

- 2) Five NDI techniques were listed by most responders as desirable, primary, and minimum techniques showing that the ability to perform ultrasonic, x-ray, visual or optical, penetrant, and tap testing is a necessary requirement for an inspection and repair facility. Figure 5.2.4 summarizes these responses. Techniques which were not considered desirable or which were borderline are also listed.
- 3) Specific technique recommendations for specified damage to specified configurations were obtained. These recommendations are summarized in Tables 5.3.15 and 5.3.16.
- 4) Technique recommendations were also made for verifying the quality of specific types of repairs. These recommendations are found in Table 5.4.1.
- 5) Water or a water-based couplant was preferred for use as an ultrasonic coupling agent.

Recommendations which follow from the above conclusions fall in several categories:

- 1) Requirements for Naval inspection facilities should include the ability to perform ultrasonic, x-ray, visual or optical, penetrant, and tap test inspections.
- 2) Current surveys concerning existing equipment should be matched against this list of techniques to determine equipment requirements.
- 3) Training of NDI personnel should be matched against the list of equipment and techniques to determine its level of adequacy. Implications from this survey are that techniques are moving toward becoming both more numerous and more sophisticated. Training of NDI personnel will have to keep pace.
- 4) Questions in this survey were designed to cover requirements for depot level inspection and repair facilities. The work should be extended to include field level inspection and repair.

FIGURE 5.2.4

RESULTS - RECOMMENDED TECHNIQUE AVAILABILITY

<u>DESIRABLE</u>	<u>PRIMARY</u>	<u>MINIMUM</u>	<u>NOT DESIRABLE</u>	<u>BORDERLINE</u>
ULTRASONIC	ULTRASONIC	ULTRASONIC	THERMOGRAPHY	N-RAY
X-RAY	X-RAY	X-RAY	ACOUSTIC HOLOGRAPHY	THERMOCHROMATIC COATINGS
VISUAL OR OPTICAL	VISUAL OR OPTICAL	VISUAL OR OPTICAL	MICROWAVE	ACOUSTIC EMISSION
PENETRANT		PENETRANT		OPTICAL HOLOGRAPHY
TAP TESTING		TAP TESTING	ION GRAPHING	DIELECTRIC
EDDY CURRENT				
SONIC RESONATOR				
LOW FREQUENCY AIR COUPLED				
EDDY SONIC				

DESIRABLE - NOT ABSOLUTELY ESSENTIAL, BUT SHOULD BE EQUIPPED TO PERFORM

PRIMARY - TECHNIQUE MOST GENERALLY USED

MINIMUM - GROUPS OF TECHNIQUES FORMING A BARE MINIMUM REPERTOIRE

NOT DESIRABLE - RECEIVED LESS THAN 25% RESPONSE

BORDERLINE - RECEIVED 25-50% RESPONSE

- 5) Several promising NDI techniques should receive more investigation and development work to move them out of the laboratory into practical, everyday usage. These include N-ray, thermochromatic coating, acoustic emission, and sonic resonance techniques. This development work will need to include both technique development and equipment development. One particularly weak area, that of field recording equipment for ultrasonic inspection, was not highlighted by the survey responses.
- 6) Certain configurations and types of damage do not appear to have reliable inspection techniques available. These are weak areas for state-of-the-art NDI. Many responders did not or were not able to recommend a technique for inspecting for moisture absorption and resin softening damage. Another area lacking firm recommendations from nearly all responders was in the inspection of laminate to metal bonds for porosity, cracks, moisture absorption, fire or heat damage, and resin softening. Another problem area needing development work did not come out in the survey responses. A method of determining the strength of a bond (not just bond or no bond) is not available.
- 7) There is no catalogue, manual, or handbook for the NDI of composite materials nor are there any established minimum detectable flaw sizes. Requirements, techniques, and detectability is going to vary with each particular composite component, but generalizations are possible for categories of construction. Preparation of general guidelines should be initiated.
- 8) NDI information should be filed as part of the computerized data bank to be established at the depot level.

The foregoing recommendations are certainly not all inclusive, nor will following them solve all inspection and repair problems. It is hoped that their consideration will, however, bring us a step closer to achieving the maintenance ideal for composite structure:

Inspection of any and all structures and repair of all damage so as to return structure to original or better condition in terms of strength, weight, aerodynamics, dynamics, corrosion resistance, fatigue strength, and fracture toughness - at a reasonable cost.

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APPENDIX A
QUESTIONNAIRE COVERING DAMAGE CLASSIFICATION,
REPAIR PROCEDURES, AND NDI

APPENDIX A
QUESTIONNAIRE COVERING DAMAGE CLASSIFICATION, REPAIR PROCEDURES, AND NDI



DEPARTMENT OF THE NAVY

NAVAL AIR REWORK FACILITY

ALAMEDA, CALIFORNIA 94501

IN REPLY REFER TO:

NARF-343-NAA

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Ser 447

22 FEB 1977

Dear

Enclosed is an industry/government prepared "comments and questionnaire" concerning Non-destructive Evaluation of Advanced Composites.

Since composite materials are finding increased applications on naval aircraft, your help in establishing a standardized approach to "evaluation of condition" on in-service or damaged structures will be appreciated.

Sincerely,

V. M. Young
V. M. YOUNG
By direction

NDE FOR ADVANCED COMPOSITES
REQUEST FOR INFORMATION

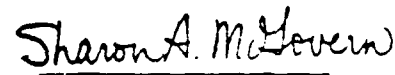
Comments & Questionnaire

The Advanced Composites Maintenance Engineering Workshop's objective was to provide information defining Navy needs for equipping Naval Air Rework Facilities to maintain and repair advanced composite structures on aircraft. During the last day's review of the workshop, a number of areas were discussed in which further information was needed. S. A. McGovern from Vought Corporation was assigned the task of surveying participants to obtain a consensus as to NDE equipment and technology the Naval Air Rework Facilities need to be able to adequately assess and evaluate damage and to inspect repairs on composite structures.

The attached NDE Questionnaire attempts to organize the information needed. Hopefully the format will require minimal time to make your contribution and will make the responses easy to compile. We would appreciate your careful consideration of the questions and your frankness in indicating both reliable techniques and areas which continue to present problems for inspection. Both the individual replies and the tabulated information will be submitted to Mr. Norman Amdur by 15 April 1977. The collected and collated information will be made available to all participants in published proceedings at the Navy's Second Annual Advanced composite Structures Materials/Processes Maintenance Engineering Workshop scheduled for 3 - 5 May 1977.

Sincerely,


Norman Amdur


S. A. McGovern

NDE QUESTIONNAIRE - MAINTENANCE AND REPAIR OF
ADVANCED COMPOSITE AIRCRAFT STRUCTURE

Company/Activity Signature Date

1. In the first column, place a check by the configurations or constructions you feel the NARF should have capability to inspect for damage.
2. In the second column, select the four most frequently encountered configurations, ranking from 1 to 4 (1 most frequent to 4 least frequent).
3. Please add any configurations needed which are not on the list.

<u>NEED TO INSPECT</u>	<u>IMPORTANCE OR FREQUENCY OF ENCOUNTER</u>	<u>CONFIGURATION OR CONSTRUCTION</u>
<input type="checkbox"/>	<input type="checkbox"/>	a. <u>Laminated</u> -
<input type="checkbox"/>	<input type="checkbox"/>	Graphite/Epoxy
<input type="checkbox"/>	<input type="checkbox"/>	Boron/Epoxy
<input type="checkbox"/>	<input type="checkbox"/>	Kevlar/Epoxy
<input type="checkbox"/>	<input type="checkbox"/>	Metal/Composite Multilayer
<input type="checkbox"/>	<input type="checkbox"/>	Composite Hybrid
<input type="checkbox"/>	<input type="checkbox"/>	Other
<input type="checkbox"/>	<input type="checkbox"/>	b. <u>Sandwich</u> -
<input type="checkbox"/>	<input type="checkbox"/>	1-Metallic Honeycomb/Composite Faces (MHC/CF)
<input type="checkbox"/>	<input type="checkbox"/>	2-Non-Metallic Honeycomb/Composite Faces (NMHC)
<input type="checkbox"/>	<input type="checkbox"/>	c. <u>Bonded</u> -
<input type="checkbox"/>	<input type="checkbox"/>	1-Metal Honeycomb/Metal Faces
<input type="checkbox"/>	<input type="checkbox"/>	2-Composite with Metallic Inserts or Shims
<input type="checkbox"/>	<input type="checkbox"/>	3-MHC/CF/Laminate Hybrid
<input type="checkbox"/>	<input type="checkbox"/>	4-MHC/CF/Metal Hybrid
<input type="checkbox"/>	<input type="checkbox"/>	5-NMHC/CF/Laminate Hybrid
<input type="checkbox"/>	<input type="checkbox"/>	6-NMHC/CF/Metal Hybrid
<input type="checkbox"/>	<input type="checkbox"/>	d. <u>Other</u> -

A number of NDI techniques are listed below along with spaces for you to add other techniques you feel should be listed.

4. In the first column, place a check beside those techniques which you feel the NARF should be equipped to perform.
5. In the second column, place a check by the technique you would recommend as the primary inspection procedure to be most generally used.
6. In the third column, place a check by the techniques which would represent the minimum techniques the NARF should have.

<u>DESIRABLE</u>	<u>PRIMARY</u>	<u>MINIMUM</u>	<u>NDI TECHNIQUES</u>
_____	_____	_____	1. Ultrasonic
_____	_____	_____	a. Pulse Echo
_____	_____	_____	b. C-Scan
_____	_____	_____	c. Thru transmission - Immersed
_____	_____	_____	d. Thru Transmission
_____	_____	_____	e. Sonic Resonator
_____	_____	_____	f. Low Frequency Air Coupled Eddy-Sonic
_____	_____	_____	2. Eddy-Sonic
_____	_____	_____	3. Eddy-Current
_____	_____	_____	4. X-Ray
_____	_____	_____	5. Neutron Radiography
_____	_____	_____	6. Penetrant
_____	_____	_____	7. Thermochromatic Coatings
_____	_____	_____	8. Visual or Optical
_____	_____	_____	9. Tap Testing
_____	_____	_____	10. Thermography (Video or Vibro)
_____	_____	_____	11. Holography (Optical) Laser
_____	_____	_____	12. Acoustic Emission
_____	_____	_____	13. Microwave

<u>DESIRABLE</u>	<u>PRIMARY</u>	<u>MINIMUM</u>	<u>NDI TECHNIQUES</u>
_____	_____	_____	14. Dielectric
_____	_____	_____	15. Ion Graphing
_____	_____	_____	16. Holography (Acoustic)
_____	_____	_____	17.
_____	_____	_____	18.
_____	_____	_____	19.
_____	_____	_____	20.

7. Complete the following Tables I and II by filling in a number(s) in each square from the preceding NDI Techniques list indicating the primary and back-up technique(s) you would recommend for inspecting the indicated configuration for the damage specified. Table III (page (5)) gives definitions of damaged types.

a. If you feel a necessity to distinguish between the selected tests based on the composite structure material of construction, i.e., boron v.s. carbon fibers, please indicate this condition.

b. If you feel there are any undefined damage types, please add the item to Tables I and/or II and define the damage type on page 5.

TABLE I

CONFIGURATIONS CONTAINING LAMINATES,
LAMINATE-LAMINATE BONDS AND/OR LAMINATE-METAL BOND

<u>DAMAGE TYPE</u>	<u>TYPE OF CONSTRUCTION</u>		<u>BONDED</u>		<u>LAMINATE TO METAL</u>	
	<u>SOLID LAMINATE</u>		<u>LAMINATE TO LAMINATE</u>		<u>LAMINATE TO METAL</u>	
	<u>PRIMARY</u>	<u>BACK-UP</u>	<u>PRIMARY</u>	<u>BACK-UP</u>	<u>PRIMARY</u>	<u>BACK-UP</u>
Delamination						
Debond						
Porosity- In Laminate In Bondline						
Vertical Bond Void						
Cracks						
Splintering						

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TABLE I - Continued

CONFIGURATIONS CONTAINING LAMINATES,
LAMINATE-LAMINATE BONDS AND/OR LAMINATE-METAL BOND
TYPE OF CONSTRUCTION

DAMAGE TYPE	<u>SOLID LAMINATE</u>		<u>BONDED LAMINATE TO LAMINATE</u>		<u>BONDED LAMINATE TO METAL</u>	
	PRIMARY	BACK-UP	PRIMARY	BACK-UP	PRIMARY	BACK-UP
Moisture Absorption						
Impact Damage						
Ballistic Damage						
Fire or Heat Damage						
Resin Softening						
Erosion						

TABLE II

CONFIGURATIONS CONTAINING HONEYCOMB CORE

DAMAGE TYPE	<u>METAL H/C CORE</u>		<u>NON-METAL H/C CORE</u>	
	PRIMARY	BACK-UP	PRIMARY	BACK-UP
Delamination Face Sheet Only				
Debond, Face to Core				
Core Damage (crushed, node separation, split)				
Core Corrosion				
Moisture in Core				
Vertical Bond Void				
Impact Damage				
Fire or Heat Damage				

TABLE III

DAMAGE TYPES

Delamination - separation of adjacent composite plies

Debond - separation at adhesive bondline

Porosity - small air pockets in the epoxy (or other) matrix or adhesive bondline

Crushed Core - core cells wrinkled or buckled

Core node separation - debond of the core ribbons at the node

Split core - core cell walls ruptured or split

Vertical bond voids - absence of a bond or bonding material between the vertical edges of two core sections or core and inserts

Cracks - fractures in either epoxy or other matrix or both matrix and fibers

Splintering - a combination of cracking and delamination of the outer fibers

Scratches, dents, gouges, nicks, holes - mechanical damage involving one or more composite plies but not caused by an armament projectile

Bondline cracks - bondline cracking as a result of strain

Core corrosion - oxidation or other chemical or electrolytic attack that adversely affects the core.

Moisture absorption - accumulation of water in pores of the composite structure or in honeycomb core cells

Impact damage - damage from foreign object (other than ballistic)

Ballistic damage - damage resulting from armament projectile strikes

Blister - void under paint or other coating

Fire or heat damage -

Resin softening - damage to the matrix resin due to inadvertent exposure to paint strippers or other deleterious solvents or chemicals

Erosion - Service wear to any exterior aircraft surface from rain, airborne dirt, dust, etc., hail stones or static discharge pitting.

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8. Below is a list of types of repair. Please place the number(s) from the NDI Technique list on pages 2 & 3 indicating the technique(s) you would recommend for inspecting each repair after it has been performed.

INSPECTION TECHNIQUE(S)

PRIMARY	BACK-UP	TYPE OF REPAIR
		1. <u>Surface Repair</u> - Coating or laminate surface erosion resurfacing with a paint, smoothing compound or resin gel coat
		2. <u>Laminate Repair</u> - Step laminate or insert installed in solid laminate skin or H/C face with no protrusion from original part surface
		3. <u>External patch</u> - Repair skin patch protruding above original part surface.
		a. <u>Titanium/fiberglass</u>
		b. <u>Graphite/epoxy</u>
		c. <u>Boron/epoxy</u>
		d. <u>Bolted titanium plate</u>
		4. <u>Core Repair</u> -
		a. <u>New core plug installed</u>
		b. <u>Substitute filler for core followed by 1, 2 or 3.</u>
		5. <u>Lightening Strike or Static Protection Repair</u>
		6. <u>Other</u>

9. For ultrasonic contact methods, what is the couplant or coupling system you prefer and why?

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10. In the space provided below, please add any comments you feel will be helpful or information you feel is needed but no other place on the questionnaire was provided.

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